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ABSTRACT

Stress-corrosion crack growth rate data obtained as a function of the plane-strain stress intensity using double cantilever beam specimens of 7079, 7075, and 7175 are presented. The effects of quenched-in residual stresses on crack growth rates in specimens of this design are discussed, and methods of eliminating the residual-stress problem are presented.

INTRODUCTION

Considerable stress-corrosion crack growth rate data for several high-strength aluminum alloys have recently been obtained by the author (1,2,3,4) using the precracked double cantilever beam (DCB) specimen shown in Fig. 1. The advantages of using specimens of this design in stress-corrosion studies and the method of obtaining the data are described in Ref. 1. By using this specimen and Eq. (1) (from Ref. 1), stress-corrosion crack growth rate data can be obtained as a function of the plane-strain stress intensity K_I.

$$K_I = \frac{vEh[3h\ (a + 0.6h)^2 + h^3]^{1/2}}{4\ [(a + 0.6h)^3 + h^2a]} \qquad (1)$$

where: v = total deflection of the two arms of the DCB specimen at the load point (centerline of loading bolt)

E = modulus of elasticity (10.3×10^6 for aluminum alloys)

h = 1/2 specimen height

a = crack length measured from load point (centerline of loading bolt)

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The procedure for obtaining the crack growth rate data is illustrated schematically in Fig. 2. The loading bolt is turned until a sharp crack is popped in from the end of the machined notch. Plane-strain fracture toughness K_{Ic} can be calculated by measuring v and a at any subsequent pop-in. After the crack has been advanced a few tenths of an inch by several pop-ins, the bolt is left fixed, giving a constant crack opening displacement (COD). The 3.5% NaCl environment is then applied. Under these conditions, the load P at the bolt and K_I at the crack tip decrease as the stress-corrosion crack length increases (Figs. 2b and 2c). The slope of the resulting crack length-time curve in Fig. 2a then gives the crack growth rate as a function of K_I. As the crack length a increases and K_I decreases, a K_I level may eventually be reached below which growth ceases or is negligible. This K_I level, designated K_{Iscc}, is shown in Fig. 2c. Use of DCB specimens is especially suited to aluminum alloys with elongated grain structures, since stress-corrosion cracking is intergranular and cracks are kept in plane by the elongated grain structure of the material.

The specimens were bolt loaded to K_{Ic} and the steel bolts were insulated by masking the bolt end of the specimens with a vinyl coating. The specimens were then placed upright (bolt end up) and several drops of an aqueous solution of 3.5% NaCl were placed in the machined slot of the specimens using a polyethylene squeeze bottle. The NaCl solution was applied three times each working day at 4-hr intervals. Crack lengths were monitored using a hand lens and ruler.

Most of the specimens used to obtain the K_I-rate (K_I versus crack growth rate) data in Refs. 1, 2, and 4 were from residual-stress-free, stretcher-straightened plate material (TX51 temper). However, a few specimens were from die forgings that contained quenched-in residual stresses. A few other specimens (from plate material) were re-heat treated as DCB specimen blanks and quenched into cold water prior to aging. Quenching produces residual compressive stresses on the surfaces of the DCB specimen and residual tensile stresses in the interior of the specimen. Such residual stresses cause crack front bowing and

geometry changes in the arms of the DCB specimen that introduce errors into K_I calculations. This report presents data showing the effects of quenched-in residual stresses and discusses methods of eliminating the problems introduced by them.

EFFECTS OF RESIDUAL STRESSES ON DCB SPECIMENS

GEOMETRY CHANGES

Double cantilever beam specimens that are re-heat treated as 1- by 1- by 5-in. blanks and cold water quenched before aging contain residual compressive stresses on the surface and residual tensile stresses in the interior. When a notch is machined into the specimen and a crack is popped in from the end of the notch, some of the internal residual tensile stresses are relaxed. The residual compressive stresses on the outside surfaces of the DCB specimen parallel to the crack plane are then able to bow the two arms of the DCB specimen apart. This phenomenon is illustrated in the re-heat-treated 7079-T6 DCB specimen in Fig. 3. The stress-corrosion crack has propagated along the entire length of the specimen. The bowing is evidenced by the greater separation of the two arms at the center of the specimen. The dark material at the bolt end of the specimen is the vinyl coating that was applied after pop-in and before the aqueous 3.5% NaCl environment was applied, to prevent any galvanic action between the steel bolt and the aluminum specimen.

Normally, the deflection v at the bolt centerline after pop-in is used in Eq. (1) to calculate K_I. It is obvious, however, that with bowed specimens such as that shown in Fig. 3, serious errors are introduced into Eq. (1) if the deflection is used. Because of the increased bowing of the two DCB arms as the crack grows, the COD near the crack tip increases; thus, the actual K_I at the crack tip is higher by some unknown amount than the K_I calculated using the deflection at the bolt centerline, which remains constant.

Once a crack has been popped in and has started to grow, the bolt can be completely removed from the specimen and the stress-corrosion crack will continue to grow owing to the effective COD from the bowing action. This is illustrated in Fig. 4, which shows both sides of an underaged 7075 DCB specimen in which the stress-corrosion crack has propagated along the entire length of the specimen despite the fact that the bolt was removed after pop-in.

CRACK FRONT BOWING

Another error is introduced into Eq. (1) from the bowed stress-corrosion crack front in DCB specimens containing residual quenching stresses. This phenomenon is illustrated in Fig. 5, which shows the fracture faces of a re-heat-treated 7075-T6 specimen from plate and a 7175-T66 specimen from a cold-water-quenched die forging. Crack advance during pop-in is more favorable in the center of the specimen, where residual tensile stresses are highest. Residual compressive stresses on the outside of the specimen, combined with the plane-stress state there, can significantly retard crack advances during pop-in and, eventually, the stress-corrosion crack growth. Since the crack lags on the surface, errors are introduced in crack length measurements made on the outside of the specimen during the test. Thus, crack length may vary along the crack front, making accurate or meaningful K_I calculations difficult.

ELIMINATING RESIDUAL STRESSES

The simplest way to eliminate the residual-stress problem is to machine specimens only from plate or extrusions that have been stretcher straightened (TX51) after solution treatment. However, if the DCB specimens must be re-heat treated, there are other ways to avoid the problem. The DCB blank can be made extra long so that after the solution treatment and quenching operation, the DCB blank can be plastically stretched 2% to 3% in tension to remove the residual quenching stresses

(the extra length is required for gripping in the tension-testing machine). After the blank is aged, the DCB specimen can be machined from the stretched portion.

The effectiveness of stress-relief treatments in reducing crack front bowing is illustrated in the four underaged 7075 DCB specimens shown in Fig. 6. The nearly complete elimination of crack front bowing is more difficult to see in the stretched specimens because they were not broken open until the cracks had grown completely through. These stretched specimens were machined from the central 5 in. of 1- by 1- by 18-in. DCB blanks that had been stretched in a 1,000,000-lb capacity tension-testing machine after quenching.

Explosive shocking after quenching was also moderately successful in removing residual stresses. The specimen shown in Fig. 6 was explosively shocked to a pressure of 1.5 times the yield strength after quenching. Explosively shocked specimens were machined from 1.5- by 5.5- by 1-in. blanks that had been shocked after quenching by using sheet explosive and a water-transmitting medium. At a standoff distance of 4 to 6 in., 0.37 to 1.85 lb of sheet explosive were used for these specimens. This procedure is not recommended, however, since it is not as controllable as stretching.

Machining of side grooves along the length of the DCB specimens after heat treatment would also help to eliminate crack front bowing by changing the stress state near the surface from plane stress to plane strain and by removing some of the material under high residual compressive stress. However, unless the specimens are also stretched after quenching to eliminate residual stresses, the arms of the DCB specimen will still bow apart, causing errors in v and K_I.

EFFECTS OF RESIDUAL STRESSES ON CRACK GROWTH DATA

It appears from Fig. 6 that the shape of a bowed crack front stays relatively constant with respect to the bowed shape at pop-in, at least

along an appreciable portion of a DCB specimen. This indicates that crack growth rates on the surface and in the center of a specimen are similar. Therefore, growth rate obtained from surface measurement of crack length would be representative of growth rate through the center of a DCB specimen.

If growth rate was always a function of K_I, it could be concluded that the equivalent K_I along a bowed crack front was the same at the center and the surface, since growth rates at the two locations are similar. However, it has been found that at the higher K_I levels, stress-corrosion crack growth rate is independent of K_I level (1,5,6,). Therefore, it cannot be assumed that K_I is constant along a bowed crack just because growth rates are similar at different locations along the crack front. Nor is the actual value of K_I on the surface or at the center of the DCB specimen known because of the bowing apart of the two arms and the resultant change in the effective COD. While it may be desirable to calculate actual K_I from measurements of the effective COD, it is sufficient here to note that actual K_I values in specimens containing residual stresses are higher than those calculated from Eq. (1) using the COD at the loading bolt.

The K_I-rate data for residual-stress-bearing and residual-stress-free 7079-T6 DCB specimens may be examined in Fig. 7. All specimens were initially machined from the same piece of 1-in.-thick 7079-T651 (stress-free) plate. One specimen was tested in the as-machined T651 temper, whereas the other two specimens were re-solution treated, cold water quenched, and aged to the T6 temper. To minimize crack front bowing in the re-heat-treated specimens, 0.1 in. of material was machined from the two faces that are perpendicular to the crack plane. Since calculated K_I values for the re-heat-treated specimens are low, as discussed, the K_I values in Fig. 7 for these specimens should be shifted to the right. This would bring the data for the residual-stress-free and residual-stress-bearing specimens closer together. Thus, all that really can be said about the effect of residual stresses on DCB specimen data is that the residual stresses cause higher effective

K_I values for a greater portion of the crack growth period. Thus, crack growth rates are, on the average, faster in residual-stress-bearing specimens, leading to shorter times for complete fracture.

The effects of residual quenching stresses on K_I-rate data for 7075 in two heat-treatment conditions are shown in Fig. 8. For clarity, only scatterbands of the data are shown, along with the scatterband for residual-stress-free 7075-T651 (1). As for 7079, actual K_I values for the residual-stress-bearing 7075 specimens are higher than those plotted. Again, this results because the K_I values were calculated from Eq. (1), using the COD at the bolt v, whereas the effective COD is higher owing to the bowing apart of the DCB specimen arms. Moving the curves for the residual-stress-bearing specimens in Fig. 8 to the right would bring them more in line with their stress-free (stretched or explosively shocked) counterparts. Note that the data for the shocked or stretched 7075-T6 material plot near the scatterband for residual-stress-free 7075-T651 material, as expected.

It should also be noted from Fig. 8 that the growth rates for the residual-stress-free material in the underaged condition (aged 72 hr at 158°F) are about an order of magnitude higher than those for similar stress-free material in the standard T6 temper (aged 24 hr at 250°F).

To illustrate more clearly the total integrated effect of residual quenching stresses on the stress-corrosion behavior of DCB specimens, the actual crack length-time curves for two underaged 7075 specimens and two 7075-T6 specimens given similar initial deflections v are shown in Fig. 9. The differences between the stretched and unstretched specimens are strikingly evident.

K_I-rate data for DCB specimens of Alcoa's new high-strength, cold-water-quenched 7175-T66 alloy may be compared with data for cold-water-quenched and non-stress-relieved 7075-T6 plate material in Fig. 10. The scatterband for residual-stress-free 7075-T651 (1) is also presented. Double cantilever beam specimens of the 7175-T66 alloy were machined

from a die forging in such a way that the crack propagated along the parting plane of the original forging. Both alloys have nearly the same composition and, undoubtedly, very similar aging treatments.* It is not surprising, therefore, that the re-heat-treated 7075-T6 and the 7175-T66 DCB specimens showed very similar growth rate behavior because both were cold water quenched. In other words, both materials contained similar residual stresses. Values of K_I plotted in Fig. 10 for both alloys are low for reasons already discussed and would be shifted to the right if correct K_I values were known. The point to be noted is that residual quenching stresses in real forgings that are susceptible to stress-corrosion cracking play an important role not only in initiating stress-corrosion cracks but also in accelerating average crack growth rates. Average growth rates are accelerated because residual quenching stresses help to maintain higher effective K_I levels during a greater portion of the growth period, thus decreasing times to total fracture in DCB specimens or in real parts.

CONCLUSIONS

1. Values of K_I calculated using crack opening displacement at the loading bolt in DCB specimens containing residual quenching stresses are lower than actual values. This results from an effectively increased COD at the crack tip caused by bowing apart of the DCB specimen arms as the stress-corrosion crack propagates through the specimen. The bowing is caused by residual compressive stresses on the surfaces of the re-heat-treated DCB specimens.

2. Residual stresses in DCB specimens can be eliminated easily by plastically deforming the DCB specimen blanks after quenching.

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*7175-T66 has lower iron and silicon contents than 7075 and is only available in die forgings. Die forgings of 7175-T66 are cold water quenched, whereas most 7075-T6 die forgings are warm water quenched.

3. K_I-rate data from re-heat-treated 7075-T6 DCB specimens that have been stretched to remove the residual quenching stresses agree with K_I-rate data from commercially produced, residual-stress-free 7075-T651 material.

4. Stress-corrosion cracks in residual-stress-free underaged 7075 (aged 72 hr at 158°F) grow an order of magnitude faster than cracks in the same material in the standard 7075-T651 temper.

5. Residual stresses in re-heat-treated and cold-water-quenched DCB specimens are sufficient to cause stress-corrosion crack growth after pop-in even after the loading bolt has been completely removed from the specimen. This results from the residual-stress pattern that causes the DCB specimen arms to bow apart as the stress-corrosion crack propagates.

6. Residual quenching stresses in actual parts susceptible to stress-corrosion cracking not only increase chances of initiating stress-corrosion cracks, but also play an important role in accelerating average growth rates. This results from increased COD and K_I levels at the crack tip due to deflections caused by the residual stresses.

7. Valuable comparisons between aluminum alloys can be made if DCB specimens of the alloys have been similarly heat treated and thus contain equivalent residual stress patterns; that is, the most stress-corrosion-resistant alloy will exhibit the slowest growth rate.

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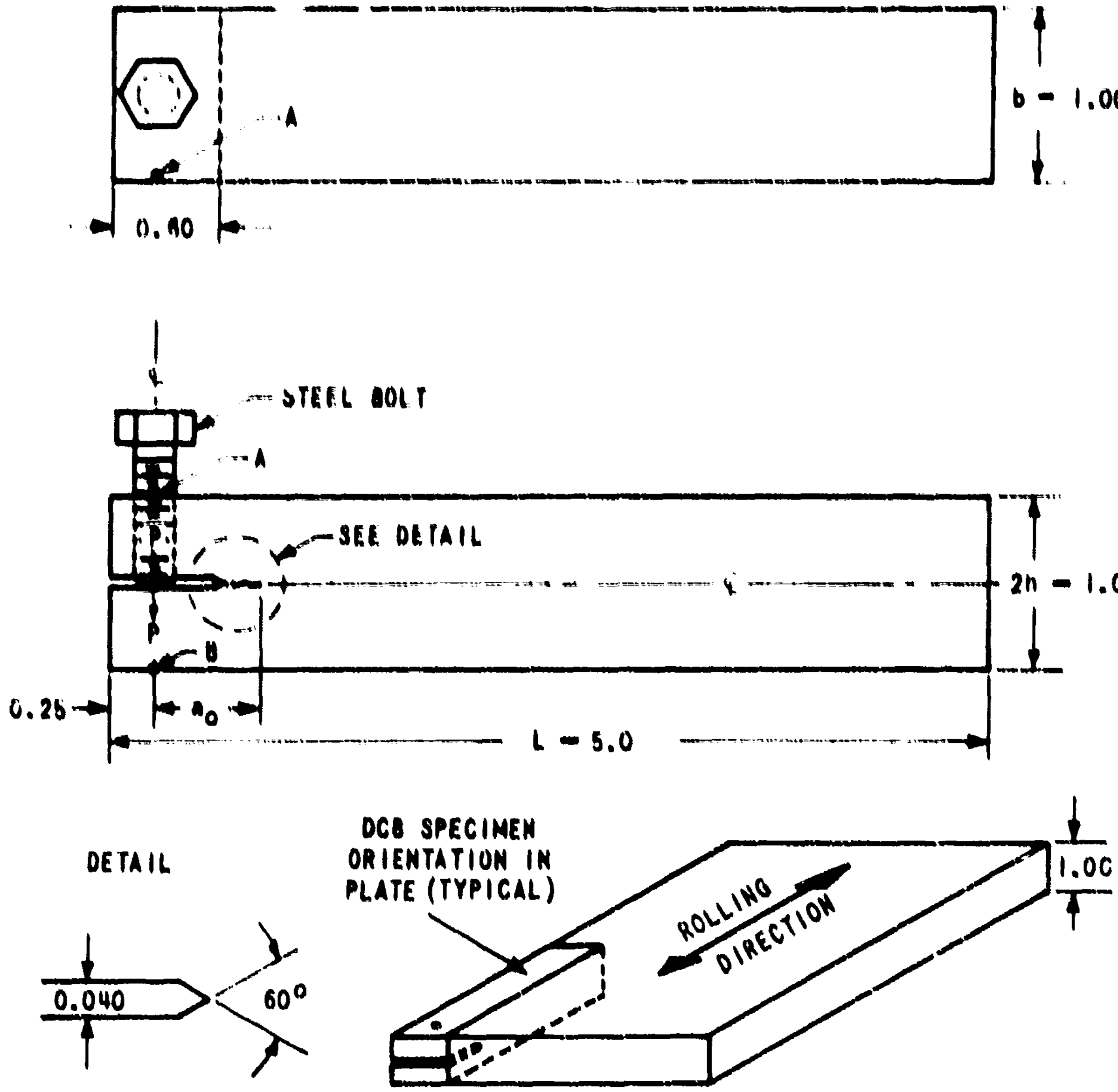


CRACK OPENING DISPLACEMENT v EQUALS THE MEASURED DEFLECTION BETWEEN POINTS A AND B ALONG THE BOLT CENTERLINE

Figure 1 Double cantilever beam specimen used for stress-corrosion testing of high-strength aluminum alloys.

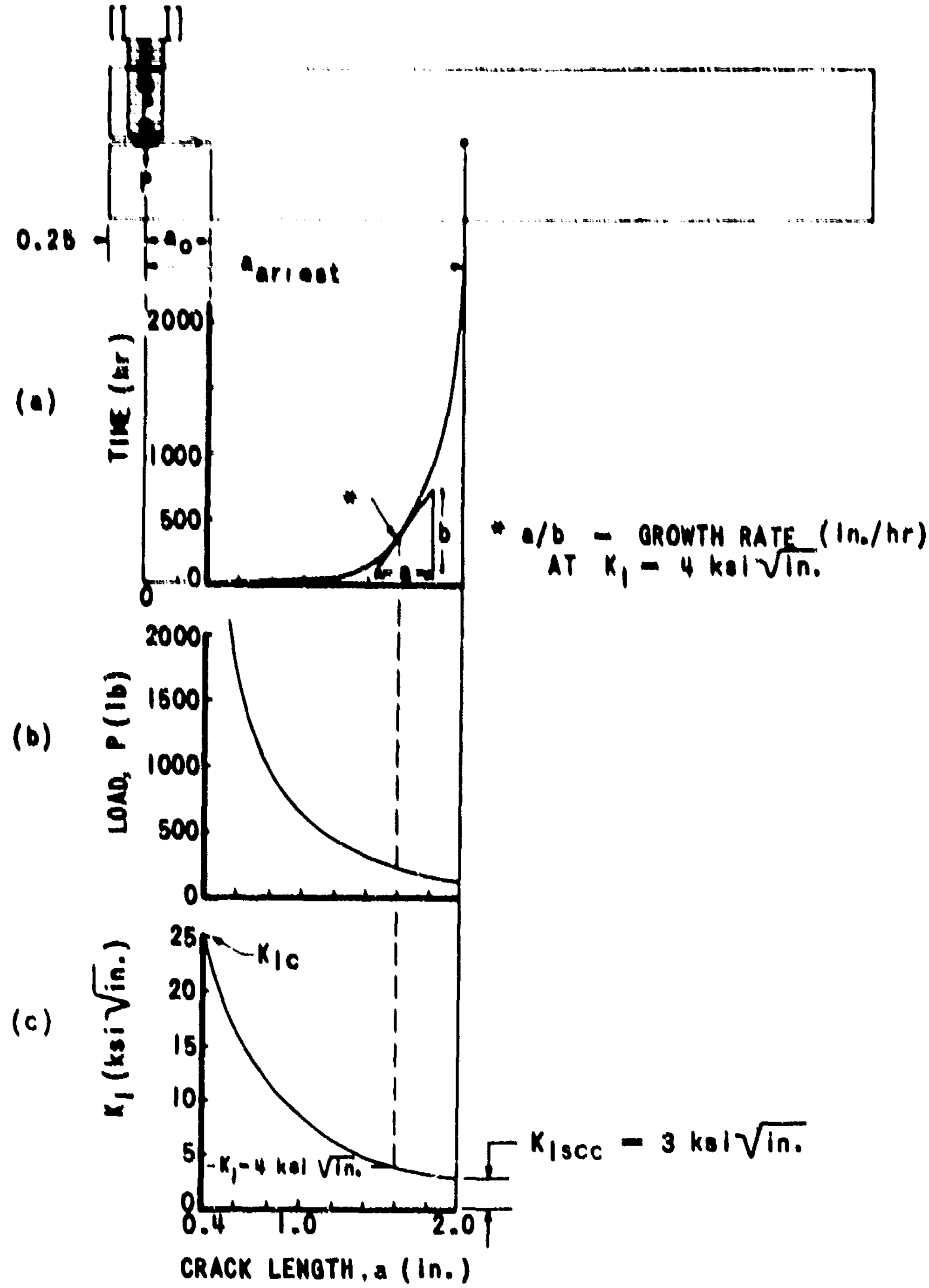


Figure 2 *Effect of crack growth on load and stress intensity under constant crack opening displacement conditions (v = 0.010 in.) in a 1- by 1- by 5- in. aluminum-alloy DCB specimen.*

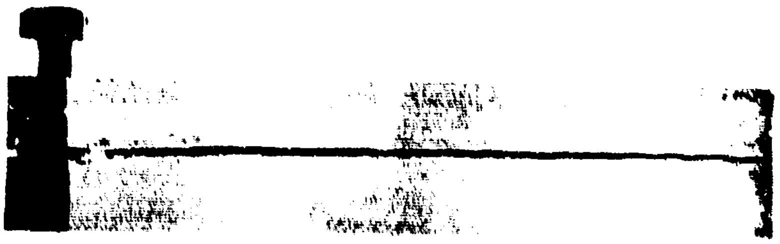
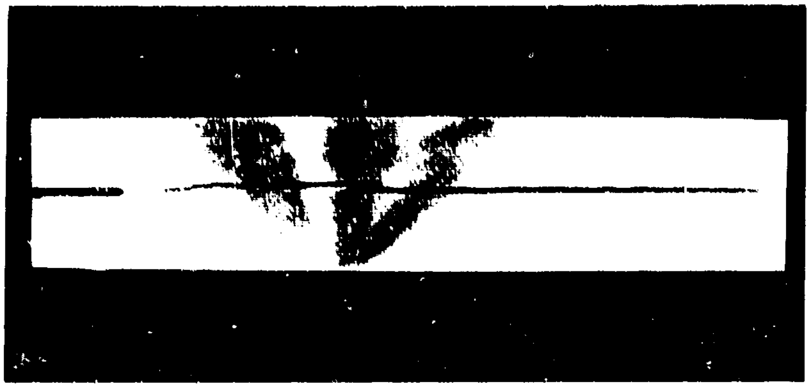
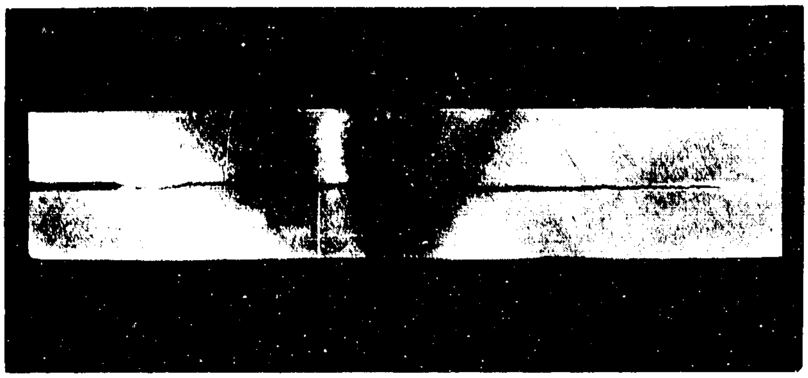


Figure 3 Bowing in a DCB specimen caused by residual stresses from re-heat treatment. Specimen was machined from 1-in.-thick 7079-T651 plate and re-heat treated to the T6 condition (830°F, cold water quenched, aged 5 days at room temperature plus 48 hr 240°F).



(a) Side 1.



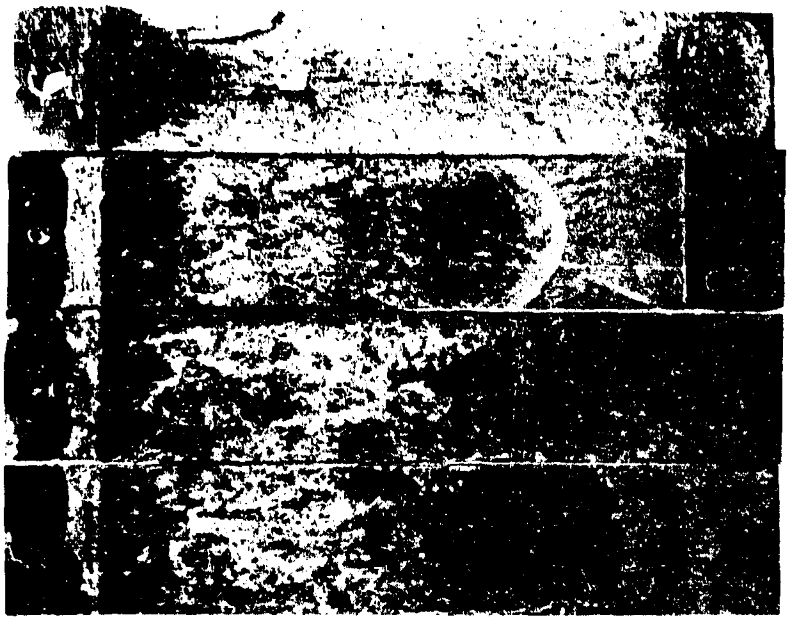
(b) Side 2.

Figure 4 *Crack propagation in a DCB specimen caused solely by the residual quenching stresses from re-heat treatment (loading bolt was removed after pop-in). Specimen was machined from 1-in.-thick 7075-T651 plate and re-heat treated to a highly susceptible condition (860°F, cold water quenched, aged 72 hr 158°F).*

(a) Re-heat treated 7075-T6 specimen from 1-in.-thick 7075-T651 plate (860°F, cold water quenched, aged 24 hr 250°F).

(b) Specimen from cold-water-quenched 7175-T66 die forging.

Figure 5 Fracture faces of two aluminum-alloy DCB specimens showing bowed crack fronts resulting from residual quenching stresses. Both the pop-in cracks and the stress-corrosion cracks are bowed.



(a) *No stress relief.*

(b) *Explosively shocked 1.5 times the yield strength after quenching.*

(c) *Plastically stretched 1% after quenching.*

(d) *Plastically stretched 2% after quenching.*

Figure 6 *Fracture faces of four re-heat-treated DCB specimens showing the relative effectiveness of several stress-relief treatments in reducing crack front bowing. Specimens were machined from 1-in.-thick 7075-T651 plate and re-heat treated to a highly susceptible condition (860°F, cold water quenched, shocked or stretched, and aged 72 hr 158°F).*

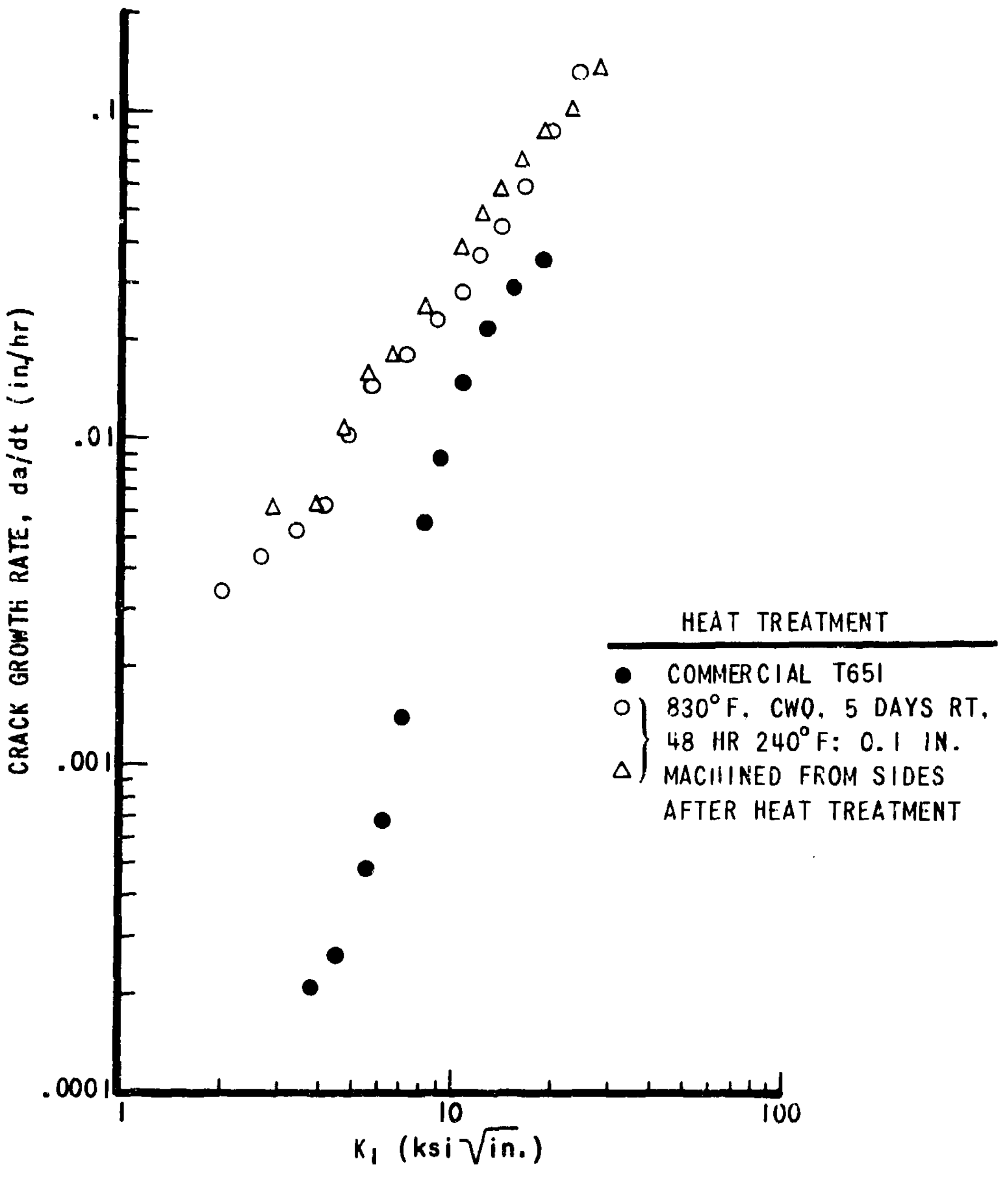


Figure 7 *K_I-rate data for residual-stress-free 7079-T651 and re-heat-treated residual-stress-bearing 7079-T6 specimens from 1-in.-thick plate.*

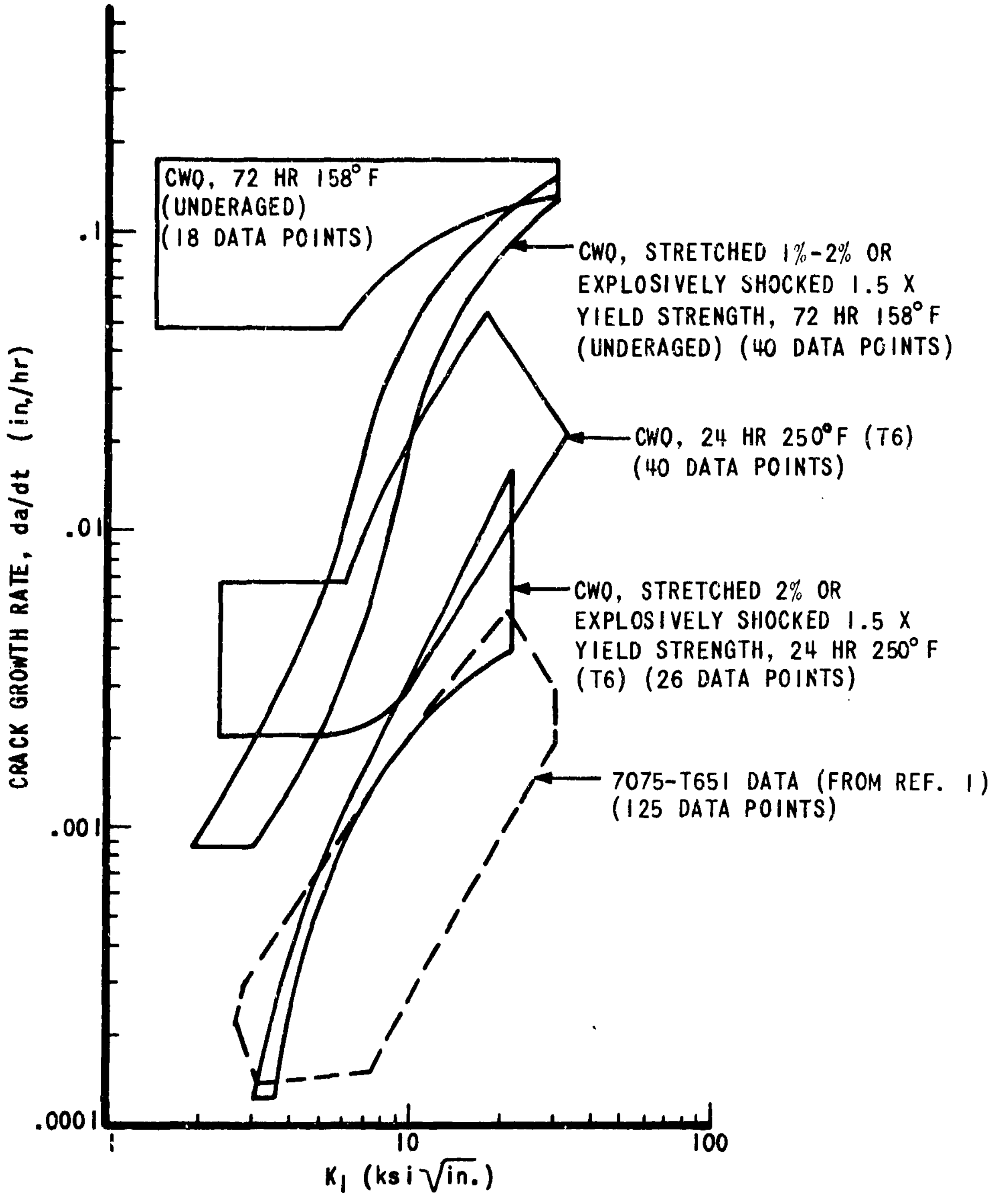


Figure 8 *Effect of stress-relief treatments on K_I-rate data for underaged 7075 and 7075-T6 DCB specimens from 1-in.-thick plate.*

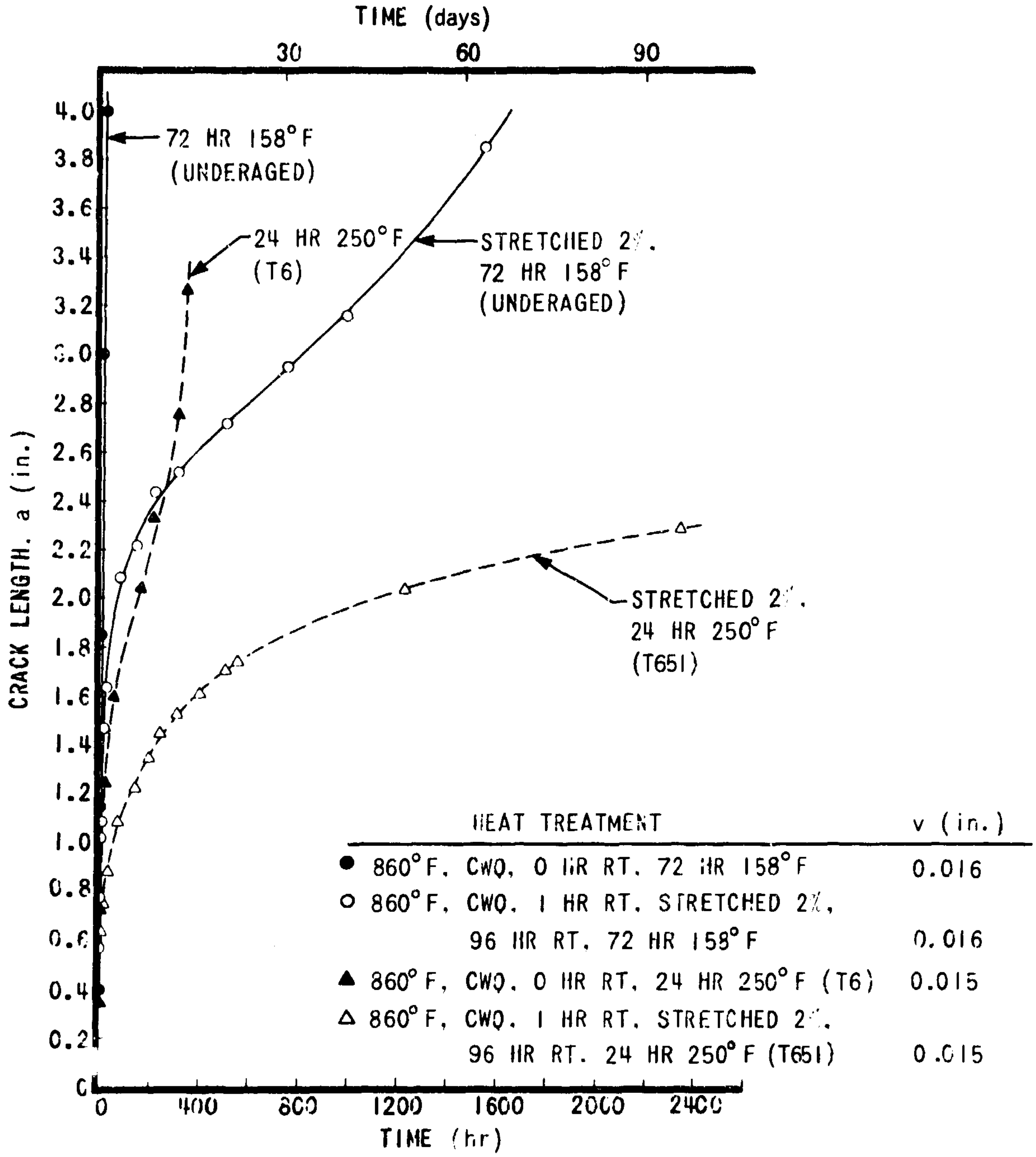


Figure 9 Effect of stress-relief treatments on crack length-time curves for underaged 7075 and 7075-T6 DCB specimens from 1-in.-thick plate.

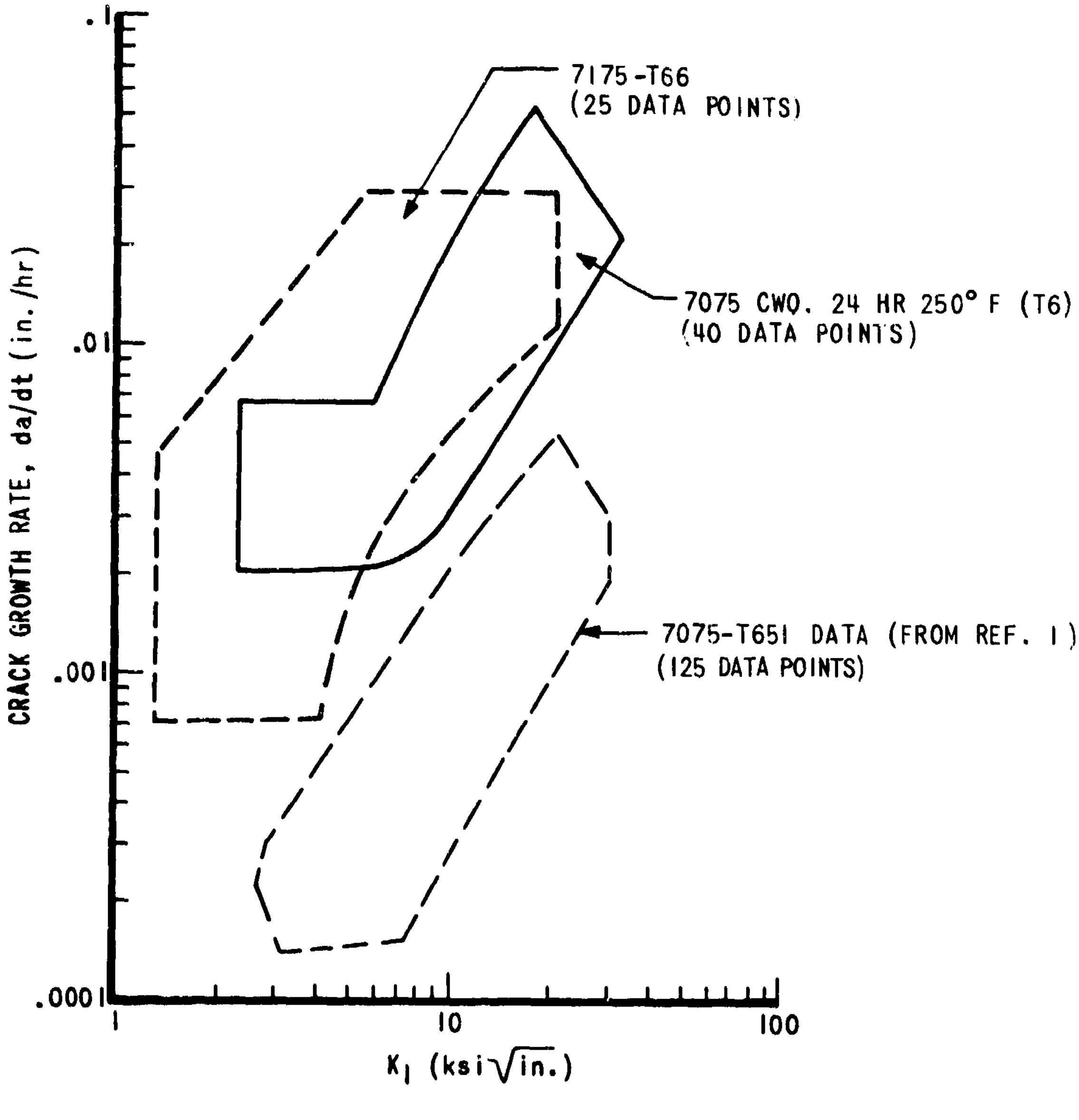


Figure 10 K_I-*rate data for 7175-T66 and 7075-T6 DCB specimens. The 7175-T66 specimens were machined from a cold-water-quenched die forging, whereas the 7075-T6 specimens were prepared from re-heat-treated and cold-water-quenched DCB blanks from 1-in.-thick plate.*

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Residual Stresses						